Evaluating WIMP Dark Matter Candidacy and Distribution with Distant Astrophysical Phenomena

Grant Proposal

Donovan Sappet

Massachusetts Academy of Mathematics and Science

Worcester, MA

WIMP Dark Matter Density Measurements in Distant Astrophysical Phenomena

Initial Dark Matter Observations

Matter is composed of subatomic particles which serve as the fundamental building blocks of our universe. The collective of all fundamental particles experimentally observed and encompassed by the current model for particle physics equations is classified as the Standard Model (SM) (*The Standard Model*, n.d.). As technological bounds are overcome and more particles are discovered, this model continues to grow. Many scientists query the existence of particles outside of the Standard Model which may govern important phenomena within the universe. Numerous theories propose that dark matter may belong to this group of particles.

The concept of dark matter was initially proposed by Lord Kelvin in 1884 following the observed discrepancy between his estimation of the mass of the Milky Way and the mass of visible stars within the galaxy. He suggested the presence of ‘dark’ objects which contribute to irregular gravitational field measurements (Kelvin, 1904). The presence of this extra force significantly affects the creation and matter distribution of galaxies, and thus learning more about the evolution of the universe and the fundamental force of gravity is intrinsically tied to the understanding of dark matter (Arbey & Mahmoudi, 2021).

Recent measurements from NASA’s Planck mission highlight the influence of dark matter on the structure of the universe, indicating that dark matter constitutes approximately 27% of the observable universe, while visible matter constitutes 5%; dark matter particles outnumber known matter by 5:1. However, other than its gravitational effect on surrounding particles, dark matter negligibly interacts with normal matter, making it incredibly difficult to detect. Due to its significant influence on the cosmological macrostructure, the true nature of dark matter remains one of the universe’s most substantial open questions; the contributor (or contributors) to the force generated by dark matter remains unknown. By leveraging quantum mechanics, computer simulations, supercollider data, and satellite images, scientists have proposed several candidates for the potential identity of dark matter.

Of the proposed theoretical dark matter candidates, those that are most intensely studied include: Massive Compact Astrophysical Objects (MACHOs), which are small stars or black holes in which little to no light reaches the area surrounding Earth; axions, particles generated by the collapse of strings (as suggested by String Theory) as well as early universe phase transitions; and Weakly Interacting Massive Particles (WIMPs) (Griest, 2002; Spergel, 1998). Of these, WIMPs have been widely considered to be the most promising candidate for dark matter and are the focus of this study.

WIMPs

WIMPs are a set of theoretical particles that are not encompassed by the Standard Model. These heavy particles have a low interaction rate with SM particles and other WIMPs (Baker & Thamm, 2018). A primary example of a weakly interacting particle is the neutrino, which does not interact with light (also referred to as a photon particle) and requires massive underground detector chambers for idenetification. Many different types of particles, including those which are related to String and related models are considered to serve as dark matter sources.

Simulations have given insight into the origin of dark matter during the early universe. Scientists theorize that these WIMP particles were thermally generated (spontaneously created during periods of extreme heat) during the period immediately following the Big Bang (Griest 2002). Due to their high density, WIMP particles experienced frequent collisions. WIMP dark matter is considered to act as its own antiparticle, and thus, during these collisions, the two particles cease to exist (through a process known as annihilation), thus lowering WIMP density (Funk 2015). As the universe cooled, WIMP thermal generation decreased at an exponential rate while annihilation continued (Arbey & Mahmoudi, 2021). Consequently, WIMP DM density decreased until the probability of a particle colliding with another particle was low enough that subsequent annihilations were unable to significantly affect overall density. This resulted in a remaining quantity of WIMP particles known as a relic abundance (Baker et al., 2020), whose average universal annihilation cross section has been mapped to $3*10^{-26}$ cm^3*s^{-1} (Funk, 2014). The gravitational effects caused by the WIMP relic abundance are likely a primary or sole contributor to the observable effects of dark matter.

Additionally, once a collision between two WIMP particles does occur, the law of conservation of energy dictates that new particles must be formed. This creation of specific product particles is referenced as an annihilation channel, which is dependent on the parameters of the equation, particularly WIMP mass (Vitale & Morselli, 2009). Efforts to detect WIMP particles are divided into three primary methods: accelerator-based detection, which leverages the LHC and other particle accelerators to probe for dark matter at specific energy ranges, direct, which utilizes large detectors and colliders to observe these particles, and indirect detection (Funk 2014), using both space and ground-based high-energy telescopes to look for WIMP annihilation channel products. The proposed study revolves around the utilization of indirect detection methods, which are described further below.

Indirect Detection of WIMPS

To analyze dark matter properties within a region of space, scientists have focused on the measurement of a particular particle—a γ-ray—which is consistently a product of WIMP annihilation, either through direct production or through the decay of other particles. Typically, γ-ray telescopes such as the Fermi LAT, H.E.S.S., Veritas, and other ground and orbit-based telescopes are used to observe the γ-ray flux in a specific region of space. (Arbey 2021). Through the differentiation of WIMP and non-wimp γ-rays, the annihilation cross section of WIMP dark matter can be approximated. Typically, the extrapolated parameter of choice is the upper bound of the 95% confidence interval of the annihilation cross section to consider uncertainties within the data, as well as the inclusion of other, lower-energy dark matter candidates. Regions of interest for these indirect detection methods include galaxy clusters and galactic centers—both of which are locations of significant DM mass—and dwarf spheroidals—small galaxies orbiting the Milky Way and larger galaxies—due to their lack of γ-rays caused by visible matter (Conrad 2015).

While successful–along with pure DM and DM-baryon simulations–in establishing widely regarded limits for dark matter mass and density, indirect nor direct detection of WIMPS have provided significant analysis of these theoretical particles to encompass the WIMPs into our physics model. Additionally, collider experiments conducted with the LHC have been unable to significantly constrain proposed WIMP DM energy values. As a result of this standstill, questions regarding the overall DM candidacy of WIMPs are now being raised (Baker & Thamm, 2018).

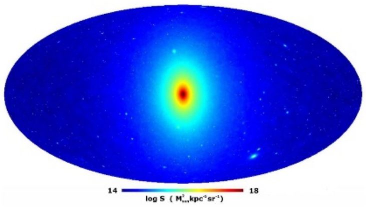

Figure 1: Simulated model of γ-ray emission from WIMP annihilation within a galactic halo (Vitale & Morselli, 2009).

Dark Matter Halo Distribution

Within the realm of indirect detection, the computation of the dark matter annihilation cross section depends upon the assumed dark matter density distribution throughout the given source. This DM distribution (often referred to as halo) lacks accurate experimental observation. As seen in Figure 1, simulations have illustrated the general shape of this halo, as well as possible dark matter substructures within the galaxy. Different equations modeling the form of the halo as a function of radius and based on different observations. However, these profile equations differ from one another. While one function—the Navarro-Frank-White profile—is considered to be the best description of the halo shape, different sources are better modeled given each different profile (Vitale & Morselli, 2009).

Section II: Specific Aims

This proposal's objective is to introduce an experiment that will analyze the properties of dark matter within distant galaxies: a minimally explored class of objects within this field. The work proposed here will provide integral research into the DM candidacy of WIMPs as well as the distribution of dark matter within a previous stage of the universe's lifetime. To achieve this, two primary goals for the study are defined below.

Specific Aim 1: Develop a DM mass-annihilation cross section graph for several distant galaxies and compare their mean parameters to the annihilation cross section of previously observed galaxies.

Specific Aim 2: Measure the dark matter γ-ray flux distribution to find the dark matter interaction rate throughout different regions of the galaxy. Subsequently, test different dark matter halo profile equations to test agreement between these values.

The expected outcome of this study is a critical analysis of WIMP candidacy as a dark matter source. If the yielded DM annihilation cross section does not significantly agree with recognized values or the dark matter evolution rates since the Big Bang, then the proposition of WIMP DM must be placed under further scrutiny. Additionally, an increased understanding of the shape of older galactic dark matter halo will provide insight into how the expansion of the universe influenced the effect of dark matter on the rotational dynamics of galaxies over time. This experiment will provide a greater understanding of the properties of WIMPs, support future research into the nature of dark matter, and push toward revealing the identity of dark matter.

Section III: Project Goals and Methodology

Relevance/Significance

The search for convincing evidence on the existence of WIMP dark matter is hindered by the lack of influential data provided by detection methods within the last several decades (Schumann, 2019). Notably, direct detection methods have been unable to definitively identify DM interaction with visible matter (Funk, 2014). The LHC and other particle accelerators have been able to lower the range of potential WIMP masses, but these measurements only cover 30% of the total WIMP mass range (Baker & Thamm, 2018). On the other hand, indirect detection methods solely examine the relationship between WIMP mass and the annihilation cross section, from which the effective DM energy range can be analyzed (Conrad, 2014). While both direct and accelerator-based detection methods are bounded by current technological means, breakthroughs in the field of indirect detection may still be made; measuring dark matter sources throughout the universe and modeling the astrophysical and particle physics properties that define the behavior of WIMPs continue to constrain the dark matter mass and annihilation cross section. While these measurements are unable to independently confirm the existence of WIMP DM, indirect detection continues to provide data regarding its properties and possible mass values.

One of the properties to which indirect detection provides more insight is the shape of dark matter galactic halos, which have never been accurately calculated within an experimental setting (Vitale & Morselli, 2009). As each of the DM halo profile equations is based on different measurements, they vary slightly from one another, particularly near the galactic center, and thus influence the observed dark matter cross section (Vitale & Morselli, 2009). Additionally, these equations may describe the distribution of dark matter throughout different galaxy classes better than others, thus the type of source must be considered when choosing which profile equation to model a specific galaxy.

Innovation

This project focuses on a previously minimally explored area for indirect DM measurements. Previous studies have typically focused on local sources of dark matter due to increased resolution and low background radiation interfering with the dark matter model calculation (Ackermann et al., 2015). Considered to be the most promising object class to impose constraints onto the dark matter particle masses, low-light dwarf spheroidal galaxies have been intensely monitored due to the high likelihood of their DM-dominated nature (Donato, 2014). As a result, distant galaxies have not been significantly explored. The proposed study examines astrophysical phenomena—up to 8 billion light years away—to provide a greater understanding of WIMP interaction in more ancient galaxies. By gauging DM parameters within these sources, a greater understanding of how the dark matter structure within galaxies evolved over time. As previous studies have not discovered the dark matter annihilation cross section of these galaxies, they may offer influential constraints on the WIMP dark matter mass range. Additionally, it may also offer details on how the general structure of dark matter halos may change over time. Because of dark energy's effects on the expansion of the universe and its driving of large astrophysical objects away from one another, the dark matter profile may have been considerably altered over the galaxy's lifetime (Arbey & Mahmoudi, 2021). By observing the radial distribution of γ-ray flux, the best-fit dark matter profile equation can be yielded. If no function fits the observed dark matter distribution rate, then it may be concluded that this dark matter property may have changed over time due to the expansion of the universe. This would be influential in understanding the properties of WIMP DM and the evolution of the LCDM model of the universe over time (Anselmi et al., 2022).

Methodology

Data Collection

For this study, galaxies of interest will be selected based on size, distance from Earth, and γ-ray flux output. Data will then be pulled from the LAT data server[1] given the galactic coordinates for this region. Python Jupyter notebook and Z-Shell with the FermiTools[2] package will then be used to perform a binned maximum likelihood analysis, yielding the probability of the collected γ-ray source belonging to the selected source. From this data, γ-ray energy-flux data will be yielded. A model for the expected γ-ray flux of the galaxy for each bin will be created and subsequently compared to the likelihood data.

The equation for the binned γ-ray flux given a solid angle ΔΩ is

$$\phi_s(\Delta\Omega) = \frac{1}{4\pi}\frac{<\sigma v>}{2m_{DM}^2}\int_{E_{min}}^{E_{max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma \times \int_{\Delta\Omega}\int_{LOS}\rho_{DM}^2(r)dl\,d\Omega' \qquad \text{(Equation 1)}$$

where the first term (to the left of the multiplication symbol) indicates the γ-ray production as defined by particle physics, while the second term considers the dark matter distribution throughout the region of interest (Ackermann et al., 2015). The LAT SCIENCETOOLS's DMFIT package will be utilized to evaluate the above function. This package computes the first term using Monte-Carlo simulations of dark matter particle collisions. However, the second term, also known as the J-factor depends heavily on the halo distribution of dark matter throughout the galaxy, $\rho_{DM}(r)$. To estimate the J-factor, the Navarro-Frank-White dark matter profile equation will be used. This process will yield a dark matter mass-annihilation cross section given a specific annihilation channel. To account for uncertainty within these cross section values, the upper bound for the 95% confidence level will be considered for future analysis The data collection process will be repeated for all galaxies of interest.

Specific Aim #1

---

[1] https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

[2] https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

The objective is to compile and compare the dark matter annihilation cross section yielded from each galaxy to previously collected dark matter measurements. To achieve this, the annihilation channel-based DM mass-annihilation cross section of each galaxy will be averaged using Pandas. These averaged values will then be plotted against annihilation cross section values from other galactic sources.

Justification and Feasibility

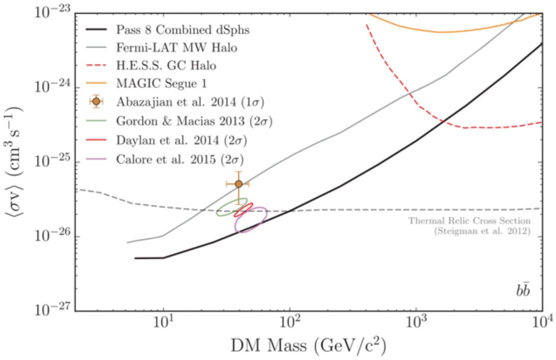

Figure 2: Graph of the DM mass vs. the upper bound of the 95% C.L. DM annihilation cross section collected by the Fermi-LAT and other high-energy telescopes (Ackermann et al., 2015).

Through the comparison of the WIMP annihilation cross section between various galactic sources, a feasible dark matter mass range can be extrapolated. For instance, Ackermann et al. compared the 95% confidence interval upper bound of the DM annihilation cross section of the dwarf spheroidal galaxies to other galactic sources (Figure 1). From this data, qualitative measurements regarding the nature of dark matter within can be made. Ackermann et al.'s data revealed that the dark matter interaction rate within the Milky Way galactic center was determined to have a consistently larger upper limit cross section due to more robust dark matter presence than that of dwarf galaxy sources. Additional qualitative measurements on the dark matter can be made using this data; the dark matter annihilation cross section of dwarf spheroidal sources less than a mass of approximately 100 GeV lay below the general thermal relic cross section rate, thus this WIMP mass was effectively eliminated from future considerations. The same process can be repeated for distant galactic sources, allowing for this evaluation to take place.

76Expected Outcomes

The overall outcome of this experiment is to evaluate the alignment of this upper WIMP annihilation cross section limit against previously collected sources. From an observation of the dark matter distribution within distant galactic sources, a similar process can be conducted. Due to the increased energy and density of matter before the dark energy-dominated expansion of the universe, it can be inferred that dark matter interacted with itself to a greater extent, thus the measured dark matter annihilation cross section should be as large as local sources. The status of this evaluation will be used to evaluate WIMP candidacy; if the dark matter cross section radius is less than that of sources such as dwarf spheroidal galaxies and galactic center measurements, then it is likely that WIMP dark matter in its current state is not a viable candidate for dark matter.

Potential Pitfalls and Alternative Strategies

To accurately achieve this aim, several factors that may impact the viability of the data shown above are considered. First, the dark matter interaction rate may contain high uncertainty due to the presence of background γ-rays (Funk, 2014). The dark matter data will be taken from a significant number of sources and subsequently averaged to assist in limiting the dark matter uncertainty. The upper and lower values of this uncertainty will also be plotted to display the potential range of the dark matter annihilation cross section of these sources.

Specific Aim #2:

The objective of this aim is to find the dark matter halo distribution within the chosen distant sources. This will be achieved by completing a radial partition of the Fermi LAT data concentric with the galaxy of interest. A distributed binned likelihood analysis will subsequently provide the γ-ray energy-flux relationship. From here, the DMFIT package will be used to compute the particle physics factor of the dark matter γ-ray flux equation (see Equation 1). The chosen dark matter distribution profiles will be leveraged to compute the J-factor term, and the resulting relationship between the mass and annihilation cross section at each radii measurement will be compared. The fit of each of the equations will then be used to calculate the profile which describes the distribution the best.

Justification and Feasibility

The chosen density profile of a dark matter source heavily impacts the J-factor of the DM γ-ray flux equation. As a result, it is important for this profile to roughly match the general shape of the source. To illustrate this, Cirelli et al. simulated the dark matter density as a function radius given different annihilation channels (Figure 2). While the profiles show universal agreement for DM density greater than a radius of 20 kpcs from the galactic center, below this value the equations diverge by up to a factor of 10,000; the choice of dark matter profile significantly affects the yielded dark matter cross section. This is imperative when considering distant galactic sources, as due to the expansion of the universe, there may be a difference in the dark matter distribution; as stated previously, the dark matter distribution within galaxies several billion away from earth was likely denser and, as a result, may not fit proposed density profile equations. As a result,

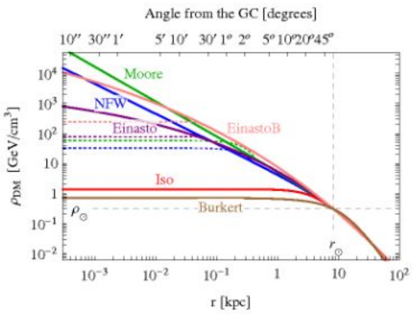

Figure 3: Dark matter radius-density relationship of different dark matter distribution profile equations (Cirelli et al., 2011).

it is beneficial to use the indirect detection of dark matter to analyze whether significant agreement with a density profile equation.

Expected Outcomes

The expected result of achieving this aim is a goodness of fit value for each dark matter distribution profile. This knowledge will be used to determine the most viable density profile equation for the source, and how dark matter evolved due to the expansion of the universe.

Potential Pitfalls and Alternative Strategies

While the distribution data collected while achieving this aim may significantly improve our understanding of dark matter, several potential risks with the data collection process need to be considered. For instance, it may be possible that no profile equation successively fits the selected data. If that is the case, then a new profile equation—one that describes this distribution within distant astrophysical sources—can be created. This will be achieved through qualitative observation or neural network development. Additionally, the galactic sources may be too distant from the Fermi LAT satellite for radial data analysis to be observed. If this is the case, the primary focus of the study will be shifted to the observation of more local extragalactic sources. While not as novel as these distant sources, a process for determining the most viable density profile equation still serves to improve human understanding of how WIMP dark matter functions within a galaxy.

Section IV: Resources/Equipment

- Python3
- Python Jupyter Notebook
- Fermitools
- FermiPy
- LAT data server
- SAO DS9

Section V: Ethical Considerations

This project does not include any ethical considerations, as testing does not include dangerous substances, or human or animal subjects. All data and packages used in this experiment are pulled from reliable internet sources and do not alter permanently alter information that affects the experience of future researchers.

Section VI: Timeline

Will add for final version

Section VII: Appendix

Will add for final version

Section VIII: References

Ackermann, M., Albert, A., Anderson, B., Atwood, W. B., Baldini, L., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Bissaldi, E., Blandford, R. D., Bloom, E. D., Bonino, R., Bottacini, E., Brandt, T. J., Bregeon, J., Bruel, P., Buehler, R., Caliandro, G. A., … The Fermi-LAT Collaboration. (2015). Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data. *Physical Review Letters*, *115*(23), 231301. https://doi.org/10.1103/PhysRevLett.115.231301

Anselmi, S., Carney, M. F., Giblin Jr, J. T., Kumar, S., Mertens, J. B., ODwyer, M., Starkman, G. D., & Tian, C. (2022). *What is flat {\Lambda}CDM, and may we choose it?* (arXiv:2207.06547). arXiv. https://doi.org/10.48550/arXiv.2207.06547

Arbey, A., & Mahmoudi, F. (2021). Dark matter and the early Universe: A review. *Progress in Particle and Nuclear Physics*, *119*. https://doi.org/10.1016/j.ppnp.2021.103865

Baker, M. J., Kopp, J., & Long, A. J. (2020). Filtered Dark Matter at a First Order Phase Transition. *Physical Review Letters*, *125*(15), 151102. https://doi.org/10.1103/PhysRevLett.125.151102

Baker, M. J., & Thamm, A. (2018). Leptonic WIMP coannihilation and the current dark matter search strategy. *Journal of High Energy Physics*, *2018*(10), 187. https://doi.org/10.1007/JHEP10(2018)187

Conrad, J. (2014). *Indirect Detection of WIMP Dark Matter: A compact review* (arXiv:1411.1925). arXiv. https://doi.org/10.48550/arXiv.1411.1925

Donato, F. (2014). Indirect searches for dark matter. *Physics of the Dark Universe*, *4*(2014), 41–43. https://doi.org/10.1016/j.dark.2014.06.001

Funk, S. (2014). Indirect detection of dark matter with γ rays. *Proceedings of the National Academy of Sciences*, *112*(40), 12264–12271. https://doi.org/10.1073/pnas.1308728111

Griest, K. (2002). WIMPs and MACHOs. In P. Murdin (Ed.), *Encyclopedia of Astronomy and Astrophysics* (1st ed., p. E2634). https://doi.org/10.1888/0333750888/2634

Kelvin, W. T. (1904). *Baltimore lectures on molecular dynamics and the wave theory of light*. C. J. Clay and sons, Publication agency of the Johns Hopkins university. http://archive.org/details/baltimorelecture00kelviala

Schumann, M. (2019). Direct detection of WIMP dark matter: Concepts and status. *Journal of Physics G: Nuclear and Particle Physics*, *46*(10), 103003. https://doi.org/10.1088/1361-6471/ab2ea5

Spergel, D. (1998, January 13). *Particle Dark Matter*. https://www.astro.princeton.edu/~dns/MAP/Bahcall/node16.html

The Standard Model. (n.d.). CERN. Retrieved November 8, 2022, from https://home.cern/science/physics/standard-model

Vitale, V., & Morselli, A. (2009). *Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope* (arXiv:0912.3828). arXiv. http://arxiv.org/abs/0912.3828